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Switching outputs in a bioenergy cogeneration project: A real options approach

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ABSTRACT

Environmental concerns have stimulated the search for economically feasible renewable energy projects. One such alternative is the use of biomass for energy generation, which has increasingly been the focus of interest. Traditional valuation methods, on the other hand, fail to capture the value of the embedded options that exist in many of these projects, which may lead to non-optimal investment decisions. In this article we analyze the feasibility of installing a cogeneration unit in an industrial plant in Brazil in order to extract value from biomass residue currently discarded, which can be used for thermal and electric energy generation. The cogeneration unit also allows the firm the flexibility to optimally choose between an increase in production or the generation of surplus energy for sale in the short term market, once additional investment in interconnection to the grid is made. We model the uncertainty over future energy prices as a mean reverting process with jumps and seasonality and the embedded flexibility as a bundle of European options under the real options approach. The results indicate that the investment in the cogeneration plant is warranted and that the option to switch outputs adds significant value to the project, which suggests that biomass residue may be a sustainable energy alternative in this case.

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1. Introduction

Environmental concerns regarding the use of conventional sources of energy have stimulated the search for renewable and cleaner alternatives. One possible solution is the use of biomass which may be able to provide up to eight times the current demand for primary energy up from the current 14% [1]. Biomass can be defined as any renewable resource derived from animal or vegetal organic matter which can be used for energy generation [2].

Within this context, Brazil is particularly well positioned to develop a significant biomass energy generation program as its temperate climate and large availability of arable land, fresh water and sunshine provide the necessary conditions for a competitive development of biomass energy on a large scale. In addition, there is an urgent need to diversify the energy matrix of the country which is highly dependent on hydro sources and thus reduce the risks of energy shortages in years of insufficient rainfall, such as

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occurred in 2001. This has led the government to create the Proinfa feed in program for small scale energy generation which resulted in 144 new ventures with a total capacity of 3300 MW, of which 685 MW is from biomass [3].

Brazil has one of the largest forest coverage in the world. This includes 6.5 million ha of high yield commercial planted forests due to a favorable climate and a continuing research program conducted by Brazilian Enterprise for Agricultural Research (EMBRAPA), a government research center affiliated with the Brazilian Department of Agriculture [4]. Nonetheless the feasibility of these projects requires extensive logistics planning in order to minimize transportation costs, and for this reason, most of these projects are located close to the biomass source. Additionally, biomass sourced energy projects typically incorporate various embedded options, such as the flexibility to choose the optimal input source, processing method or output depending on current market conditions. While these options may add value to the project, traditional valuation methods fail to capture their impact on the feasibility of the project, which may lead to non-optimal investment decisions.

Currently there are 447 biomass power plants in operation in Brazil with an installed capacity of 9900 MW, mostly from sugarcane bagasse. More recently, in August 2013 two wood biomass projects with a combined capacity of 300 MW supplied by 55,000 ha of dedicated eucalyptus forest farms won for the first time a 25 year energy auction contract [5].

Eucalyptus biomass presents several competitive advantages. It can grow over a wide variety of soils, especially degraded pastures or lands of low economic value and across different regions of the country, and thus be an important driver of growth that does not compete with the use of land for food crops or livestock. Given that production costs are mostly in local currency, it is also not subject to exchange rate risk compared to other thermal energy sources such as coal and gas. In addition, Eucalyptus biomass is environmentally friendly, has high energy density, is easy to stock, is non-perishable and the energy generation technology is well known.

Another industrial use of Eucalyptus is as a source of raw material for the production of medium density fiberboard (MDF) wood panels. In this industry a significant amount of residue is generated during the mechanical, physical and chemical processing of the eucalyptus trees, both in the field and in the factory. Residues such as leaves, branches and undersized or low quality logs are left over during the extraction process can amount for up to 20% of the total mass of the tree, while further processing during the production phase can add another 20–30% to the total residues depending on the end product. Part of this low value residue is used as fuel for the generation of the thermal energy required for the production process and the surplus is discarded. In addition to thermal energy, the plant also requires electric energy which is usually purchased from the local utilities company and which represents a significant portion of the final cost of the product [4].

In this paper we analyze the economic feasibility of investing in a cogeneration unit to produce electrical and thermal energy from forestry biomass residues for an MDF wooden panel plant, which complemented by natural gas, allows the plant to be self-sufficient in its energy needs. The cogeneration plant would also allow the wood chips currently used for thermal power generation to be directed to other uses of higher aggregated value such as MDF panel production or the generation of surplus energy that can be sold on the short-term market, once additional investment in grid interconnection is made.

The firm benefits from this investment in two ways. First, by saving on the purchase of electric energy since the unit is now energy self-sufficient. Second, from the managerial flexibility to choose the best alternative use for the wooden chips either for the manufacturing of wooden panels or for the generation and sale of electrical energy. The flexibility to switch outputs depending on market conditions in order to maximize returns has option like characteristics, and we analyze this case under the real options approach. This flexibility also allows the firm to diversify its revenue sources and incorporate a new business model to its operations.

We assume that the main project uncertainty is the highly volatile price of electricity, as it represents one of the major input costs of the plant and, once the cogeneration unit is in place, also a potential source of revenues. Due to the strong hydro portion of the electrical energy supply in Brazil and its dependence on rainfall, electrical energy prices also show a distinct seasonal behavior. Thus, we model the short term electricity prices as a mean reverting process with jumps where we incorporate into the model the impact of seasonal factors in the price volatility, which to the best of our knowledge is an original contribution. We also assume that the optimal chip use can be decided independently on a monthly basis under a short term contract, which allows this flexibility to be modeled as a bundle of European options and we solve with a Monte Carlo simulation under the risk neutral measure.

Real options theory has been widely used to analyze renewable energy projects [6–10]. Venetsanos et al. [11] applied real options analysis to value power generation projects from renewable energy sources within the newly deregulated electricity market in Greece. Kjærland [12] presents an assessment of renewable investments in Norway using the Dixit and Pindyck [13] real options approach and analyze the relation between optimal decision to invest in hydropower plants and electricity price level. Kumbaroglu et al. [14] developed a dynamic programming framework based on real options approach, to assess investments flexibilities of different renewable generation technologies of the Turkish electricity market. The diffusion and competitiveness of these technologies are impacted by uncertainties which could not be modeled by the traditional valuation techniques as the discounted cash flow method.

Araujo et al. [15] show that the upgrade in cogeneration equipment in a sugarcane processing plant adds flexibility and value to the firm. Arenaro et al. [16] analyze a sugar and ethanol production plant in Brazil which has the option to expand capacity and add a cogeneration plant that would allow the firm to sell surplus energy into the grid, where commodity and energy prices are modeled as a mean reverting diffusion process. Tolis et al. [17] investigated the economic aspects to handle in a more effective way with the problems arising from the stochastic nature of significant cash flow contributors' evolution like electricity, fuel and CO_2 allowance prices, using the real option method in a comparative model of locally available renewable and conventional fuels. They also indicate that many renewable energy projects have embedded flexibilities that can only be modeled and valued under option pricing methods. Martínez-Ceseña and Mutale [18] developed an advanced real options methodology to assess renewable energy generation project planning, considering as case study a hydropower plant using a dynamic programming model to determine the optimal decision of investment timing and project design. The authors also used Monte Carlo simulation to calculate the expected project value under uncertainty when implementing the investment and conclude that real options modeling can improve the economic analysis of renewable energy projects.

Although there is an extensive literature on the application of real options in renewable energy projects, the use of switch option models is still scarce. Bastian-Pinto et al. [19] provide a valuation of the flexibilities available in a sugarcane mill which can optimally switch production between sugar and ethanol, depending on market conditions. In a similar fashion, Brandão et al. [20] show that the diversity of inputs available for the production of biodiesel provides valuable input switch options. Detert and Kotani [21] addressed the investment decision under uncertainty considering the switch between the continuing use of coal generation system and renewable energy power

plants investments in emerging economies. The results of study revealed that real option methodology allows optimal timing information to investment decision, providing significant informations for policy makers. Yu et al. [22] analyzed the Spanish electricity market, in which a "switchable tariff" would provide the renewable power generators the flexibility to choose between the regulated tariffs for fixed generation and the free negotiation in which the price is subject to variations to the spot electricity market. In a more recent study, Varympopiotis et al. [23] conducted a feasibility analysis of a thermal power plant in Greece which has the flexibility to switch between different available fuels, depending on market and technical uncertainties.

Uncertainties related to price series are also modeled to support real options analysis. Early attempts to model electricity prices applied models developed for the financial markets, with mixed success [24]. Models developed in the literature for storable commodities such as oil and gas, as in Pindyck [25], are also not adequate for electricity markets, since the classic quantitative tools frequently rely on assumptions of normality, independence of returns and homoscedasticity which are rarely found in this industry. Kaminski [26] concluded that GBM and simple MRM diffusion processes are inadequate for the modeling of spot energy prices, and suggested that jumps and heteroscedasticity be included in these models.

Compared to other commodities, electricity price series possess unique features such as high volatility and presence of strong peaks due to the impossibility of storage, demand uncertainty and price inelasticity [27–29]. The problem is that most often than not, dramatic changes in price level followed by a similarly drastic return to the previous levels resembling price spikes tend to occur with relative frequency in electrical energy markets. One solution is to add the possibility of jumps to the model. This characteristic has been incorporated by researchers such as Clewlow et al. [30], Hambly et al. [31] and Higgs and Worthington [32] with interesting results, although the lack of consistency and randomness remain a challenge [33]. In the case of Brazil, factors related to hydrology, transmission constraints and the availability of reservoirs for water storage are the key drivers of electricity prices.

Energy models with two or more factors have also been analyzed [34,35] with the objective of separating the mean reversion process from the jump/spike components. Higgs and Worthington [32] state that one advantage of these models is that the jump/spike can be removed from the price series and treated independently. On the other hand, these models do not allow for the multiple consecutive jumps/spikes that are observed in some historical electrical energy series. Lucia and Schwartz [36] examined the behavior of energy prices through one and two factor diffusion models extending the method proposed by Schwartz e Smith [37] to include a deterministic seasonality function. None of these models, on the other hand, adequately model the distinct characteristics of hydro based Brazilian electricity market.

This paper is organized as follows. In Section 1, we discussed the context of this study and the literature on the use of option pricing methods for renewable energy projects and the modeling of energy prices. In Section 2 we present a forestry biomass energy cogeneration project for a wood panel manufacturing and in Section 3 we develop a stochastic valuation model that addresses the short term energy price uncertainty and the managerial flexibilities embedded in the project. In the following section we present our results and finally we conclude.

2. A biomass cogeneration project

The use of biomass residues for energy generation through cogeneration is an alternative that has been increasingly adopted by many industries, allowing them to reduce their energy costs and, in some cases, sell the energy excess in the market. The forestry industry is one that has been increasingly investing in cogeneration processes. This industry is characterized by the generation of significant amounts of residue during the mechanical, physical and chemical processing of the wood logs [38].

We consider a typical wooden panel plant factory that produces MDF from eucalyptus logs and uses part of the biomass residue as a source of thermal energy for the production process. Production of MDF panels begins with the chopping of eucalyptus wood logs into small fragments with an average thickness of less than 1 cm and a surface area between 6 and 10 cm² known as chips. The chips are then pre-heated under saturated steam at a temperature of 150 °C which turns them into a pulp that is further diluted in water, resins and other additives. The resulting fibers are then compressed at high temperatures to eliminate water and to form the MDF panels.

Industry data for a MDF plant was based on information available from annual reports of publicly traded firms in this industry, industry experts and authors such as Juvenal and Mattos [39] and Bom [40]. Table 1 shows a summary of the main characteristics of a typical MDF plant in Brazil:

In this process, wood chips are used both as input for the production of MDF and also as fuel for the boilers that generate thermal energy in the form of steam, hot air and hot water to dry the wood fibers, as shown in Fig. 1.

Energy cogeneration is the simultaneous production of two or more forms of energy such as heat and electromechanically energy from the same input source. In general, the term is applied to the production of thermal and electrical energy from a single primary source of energy. Energy costs can be significantly reduced by investing in an energy cogeneration unit fueled by natural gas and wood residues from the MDF processing plant which will provide both electrical and thermal energy. This allows the firm to be energy self-sufficient and for a more rational and efficient use of the chips currently used to generate thermal energy by diverting them to MDF production. Alternatively, the chips can be used in the cogeneration process to generate surplus energy for sale in the spot market (see Fig. 2).

The managerial flexibility to choose the optimal use for the wood chips currently used for thermal energy generation can be modeled as an output switch option where the required investment in the interconnection to the grid is the cost of the option, and the underlying uncertainty is the future evolution of short term energy prices. We assume that the decision to switch wood chip use can be made independently and on a monthly basis, which allows this flexibility to be modeled as a bundle of European options and solved with a Monte Carlo simulation under the risk neutral measure. Energy price uncertainty is assumed to be the short term price (PLD) which corresponds to the price of energy in the Brazilian spot market. Given that there is no future market or

Table 1
MDF Plant parameters and data.
Source: Industry experts, Juvenal and Mattos [39] and Bom [40].

	Item	Data
	Daily operation time	24 h
(1)	MDF production capacity	28,000 m³/mo
(2)	Actual MDF production	21,934 m³/mo
(2)/(1)	Efficiency	78.33%
(3)	MDF chip demand	44,185 m³/mo
	Electrical energy demand	8754 MWh/mo
(4)	Steam demand	49,144 t/mo
(4)/(2)	Tons of steam per m³ of MDF	2.24 t/m³
(5)	Thermal energy chip demand	20,143 m³/mo
(3)+(5)	Total chip demand	64,392 m³/mo
(3)+(5)/(2)	Total chip demand per m³ of MDF	2.93 m³

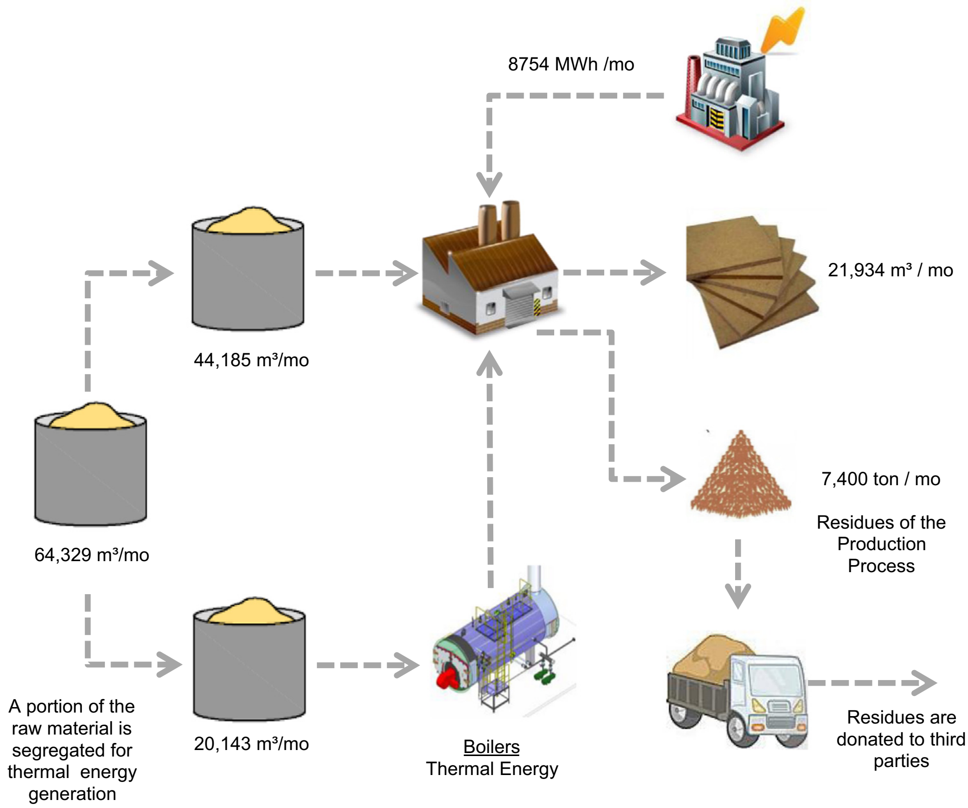

Fig. 1. Current flow of MDF production using wood chips fuel for the boilers that generate thermal energy.

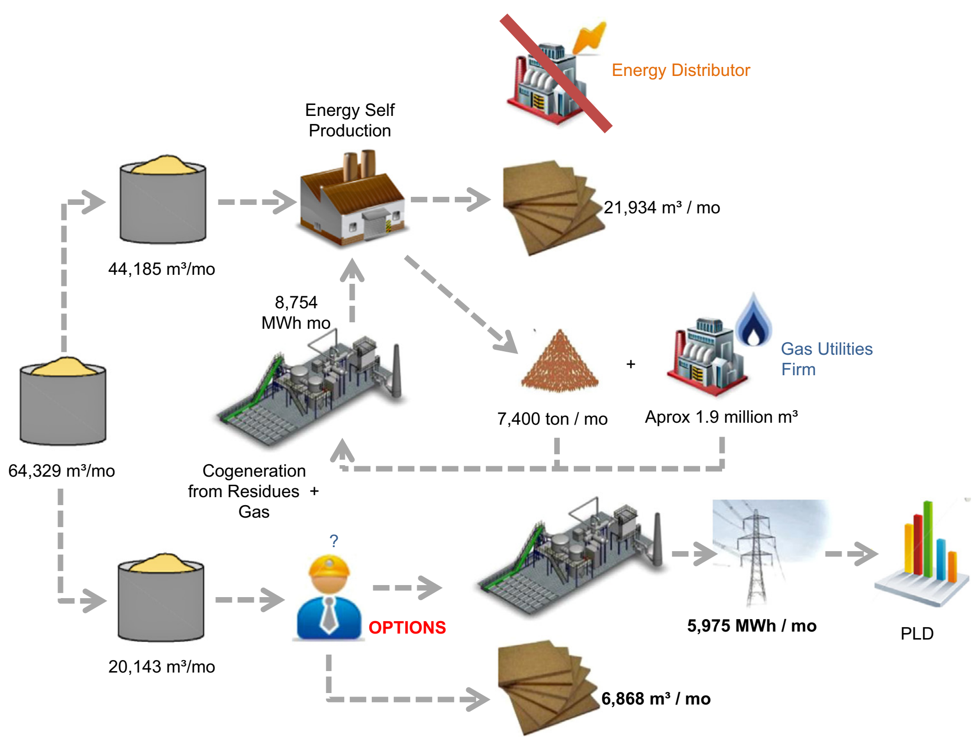

Fig. 2. Proposed flow of production with flexibility.

any reliable historical series of MDF panel prices, we assume a constant price for this product. For the traditional valuation of the investment in the cogeneration plant we assume a life of 10 years.

The investment costs for the cogeneration unit, including the generation and distribution of steam and electrical energy is R$ 52.7 million (1 R$ = 0.40 USD). Once the unit is built, it is necessary to connect it to the commercial grid at an additional cost of R$ 10 million if sales of surplus energy are to take place. Table 2 contains the main parameters, variables and assumptions used for the valuation of the cogeneration project and Table 3 shows the

structure of the free cash flow to the firm for each of the options analyzed.

3. Valuation model

We assume that the main source of uncertainty is the short term electricity price (PLD), and base our model on the Schwartz [42] mean reverting model 1 diffusion process $dS = \eta(\alpha - \ln S)S\,dt + \sigma S\,dz$. It is generally assumed that $\alpha = \ln(\overline{S})$, which provides $dS = \eta(\ln \overline{S} - \ln S)S\,dt + \sigma S\,dz$, where

S is the stochastic variable;
$\overline{S}$ is the long term equilibrium level of the stochastic variable;
η is the reversion speed;
σ is the volatility of the process;
dz is the standard Weiner process with a normal distribution $dz = \varepsilon\sqrt{dt}$, $\varepsilon \sim N(0,1)$;
dt is the infinitesimal time increment of the process.

In order to simulate the stochastic variable and determine the parameters of the process, the infinitesimal time increment dt is modeled as a discrete time interval Δt, as proposed by Bastian-Pinto [19] and shown as

$$S_t = \exp\left\{ \ln\,[S_{t-1}]e^{-\eta\Delta t} + \left[\ln(\overline{S}) - \frac{\sigma^2}{2\eta}\right](1-e^{-\eta\Delta t}) + \sigma\sqrt{\frac{1-e^{-2\eta\Delta t}}{2\eta}}N(0,1)\right\} \tag{1}$$

Table 2
Assumptions for the valuation model.
Source: Bom [40] and experts in the field.

Initial PLD	126.77
COGS	60%
Avoided purchases	8754 MWh/mo
Energy sales	5975 MWh/mo
Fees	21.65%
IR+CSSL	34.00%
G&A	6% CAPEX/mo
Variable cost gas	R$ 0.45 R$/m³
Volume of gas	1,883,630 m³/mo
Interest rate	0.76%/mo
Additional MDF production	6868 m³
MDF sales price	R$1200/m³

Parameter estimation can be made regressing series S_t, as shown below

$$\ln(S_t/S_{t-1}) = \underbrace{(1-e^{-\eta\Delta t})(\ln \overline{S} - \sigma^2/2\eta)}_{a} + \underbrace{(e^{-\eta\Delta t}-1)\ln S_{t-1}}_{b-1} \tag{2}$$

where the parameters of speed of reversion, volatility and long term mean are given by Eqs. (3), (4) and (5), respectively

$$\eta = -\ln(b)/\Delta t \tag{3}$$

$$\sigma = \sigma_\varepsilon\sqrt{\frac{2\ln b}{(b^2-1)\Delta t}} \text{ where } \sigma_\varepsilon \text{ is the standard error of the regression} \tag{4}$$

$$\overline{S} = \exp\left[\frac{a}{1-b} + \frac{\sigma^2}{2\eta}\right] \tag{5}$$

Substituting Eqs. (3) and (4) into (5) we arrive at

$$\overline{S} = \exp\left[\left(a + \frac{\sigma_\varepsilon^2}{(1+b)}\right)/(1-b)\right] \tag{6}$$

In order to obtain the risk neutral simulation of the process required for option pricing, it is necessary to subtract the normalized risk premium $[\mu - r/\eta$ or $\pi/\eta]$ from the long term mean, where μ is the risk adjusted discount rate, r is the risk free interest rate and π is the risk premium, as shown below

$$S_t = \exp\left\{ \ln\,[S_{t-1}]e^{-\eta\Delta t} + \left[\ln(\overline{S}) - \frac{\sigma^2}{2\eta} - \frac{\mu - r}{\eta}\right](1-e^{-\eta\Delta t}) + \sigma\sqrt{\frac{1-e^{-2\eta\Delta t}}{2\eta}}N(0,1)\right\} \tag{7}$$

In order to model the more sudden changes in prices that are observed in the market, we include a jump process $k\,dq$. Due to the ability of the system to store energy in the reservoirs, short term prices do not present the spike behavior which is characteristic of non-hydro based markets, but tend to increase slowly but steadily as reservoir levels fall below expected values. Thus we adopt nominal values of positive jumps in order to avoid the possibility of negative energy prices where the random jump k is modeled as a lognormal distribution. The jumps are modeled in discrete time and their frequency is given by the random binary variable dq. Thus, jumps will only occur when dq is equal to 1, and the process becomes a simple mean reverting process whenever dq is zero. The general jump diffusion process for energy prices (S) can then be modeled as $dS = \eta(\ln \overline{S} - \ln S)S\,dt + \sigma S\,dz + k\,dq$ where $k \sim L(\overline{\kappa}, \delta)$ and $\overline{\kappa}$ and δ are respectively the mean jump size and the standard

Table 3
Switch option: free cash flow for each alternative.
Source: based on Brigham and Gapensky [41].

MDF production	Energy production
Total revenues (A+B)	**Total revenues** (A+B)
(A) Avoided energy purchases	(A) Avoided energy purchases
(B) Sales of MDF panels	(B) Sale of surplus energy
(−) Fees	(−) Fees
(=) Net revenue	**(=) Net revenue**
(−) COGS and variable costs	–
(=) Net operational costs	–
(−) G&A and sales expenses	(−) G&A, variable costs and others
(=) EBITDA	**(=) EBITDA**
(−) Interest, depreciation and amortization	(−) Interest, depreciation and amortization
(=) EBT	**(=) EBT**
(−) Income taxes	(−) Income taxes
(+) Depreciation	(+) Depreciation
(=) Free cash flow	**(=) Free cash flow**

deviation of the jump, and

$$dq = \begin{cases} 0 & \text{if} \quad \gamma > \phi\, dt \\ 1 & \text{if} \quad \gamma \le \phi\, dt \end{cases}$$

where $\gamma \sim U(0,1)$ and ϕ is the frequency of the jumps.

Accordingly to the discretization process, we again consider Δt in terms of discrete time interval for risk neutral simulation of energy spot prices with jumps given as

$$S_t = \exp\left\{ \ln\,[S_{t-1}]e^{-\eta\Delta t} + \left[\ln(\overline{S}) - \frac{\sigma^2}{2\eta} - \frac{(\mu-r)}{\eta}\right](1-e^{-\eta\Delta t}) + \sigma\sqrt{\frac{1-e^{-2\eta\Delta t}}{2\eta}}N(0,1) + L(\overline{\kappa},\delta) \therefore (\gamma_i < \phi\Delta t) \right\} \tag{8}$$

Considering that the jumps can only be observed as part of a time series that include the mean reverting behavior, is necessary to filter out the jumps of the series and determine the frequency ϕ before the estimation of the mean reversion parameters. For markets where energy prices have instantaneous changes with strong reversion to previous levels which are characteristic of spikes, Clewlow et al. [30] suggest the use of a recursive filter. For the case of the Brazilian energy markets where the prices are weekly rather than hourly and prices do not present instantaneous changes, this model is not appropriate. Accordingly, we assume as a jump any price increment above R$ 200.00 per MWh.

The predominantly hydro Brazilian electrical system is structured so that the seasonal uncertainty over the amount of yearly rainfall is minimized through the construction of large reservoirs where water can be stored during the wet season for energy generation in the dry season. Due to this, energy prices also present a strong seasonal volatility as deviations from the expected rainfall can have a significant effect on prices. In order to verify this, we segmented the energy price series into 12 monthly clusters where each cluster represents one particular month of the year over the 10 year period. For each cluster the mean and standard deviation were determined and the results are shown in Table 4.

The analysis shows that price volatility increases during the wet season, which indicates that there is a need to incorporate this factor into the prices models in Brazil. We incorporate this effect by adapting the stochastic price process with a seasonality factor ξ applied over the volatility parameter of the risk neutral simulation process as shown in Eq. (9). This adjustment helps solve the homoscedasticity limitation which is prevalent in energy models.

$$S_t = \exp\left\{ \ln\,[S_{t-1}]e^{-\eta\Delta t} + \left[\ln(\overline{S}) - \frac{\xi_i^2\sigma^2}{2\eta} - \frac{(\mu-r)}{\eta}\right](1-e^{-\eta\Delta t}) + \xi_i\sigma\sqrt{\frac{1-e^{-2\eta\Delta t}}{2\eta}}N(0,1) + L(\overline{\kappa},\delta) \therefore (\gamma_i < \phi\Delta t) \right\} \tag{9}$$

The historical series of the short term spot prices (PLD) from March 2002 to July 2013 was obtained from the Electrical Energy Clearing Chamber (CCEE), and adjusted from weekly to monthly basis. The series was adjusted by the IGP-M (FGV) price index to July 2013 values and its descriptive statistics are shown in Fig. 3:

The Seasonality Factors (ξ) were determined as the ratio of the monthly standard deviation and the standard deviation of the full PLD series as shown in Table 4. Model parameters were estimated from the adjusted PLD price series. The search for jumps identified (10.49%) prices considered to be outliers, which were substituted by the ceiling price of R$ 200.00. The estimation process followed Bastian-Pinto [19] and the results are shown in Table 5.

The risk premium was determined following the procedure suggested in Freitas and Brandão[44] where the present value of the deterministic case without options discounted at the risk adjusted rate must be the same as the risk neutral case where the adjusted long term mean. The solution to this is obtained using the Goal Seek tool in Excel®.

Table 4
Seasonal statistics of PLD prices.
Source: based on PLD price series of the Brazilian Electrical Energy Clearing Chamber – CCEE [43].

	Jan	Fev	Mar	Abr	Mai	Jun	Jul	Ago	Set	Out	Nov	Dez
Mean	103.3	77.2	80.2	61.2	80.8	68.2	71.5	68.3	83	90.9	103.5	75.3
Std dev	193.8	123.7	99.1	68.4	95.8	50.5	56.8	57.4	81	92.8	118.7	88.3
ξ	1.9	1.6	1.2	1.1	1.2	0.7	0.8	0.8	1.0	1.0	1.1	1.2

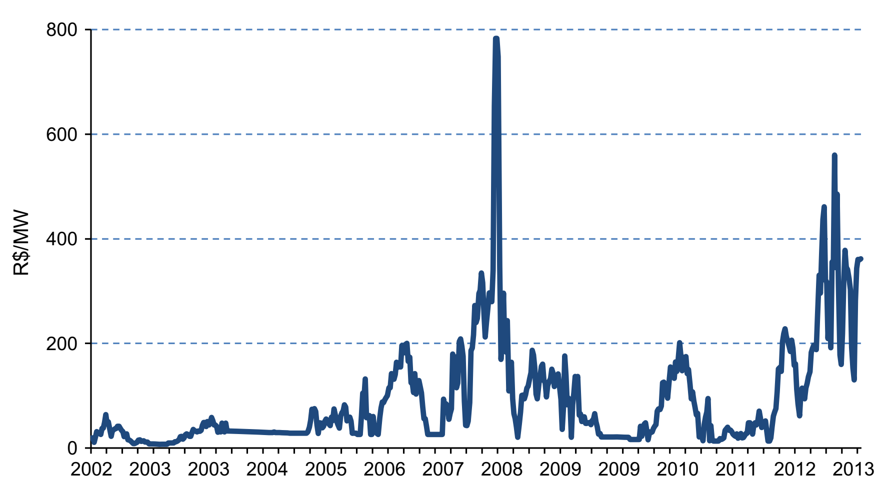

Fig. 3. Historical series of the Brazilian short term spot prices (PLD) from March/2002 to July/2013.
Source: Brazilian Electrical Energy Clearing Chamber – CCEE [43].

4. Results

The traditional discounted cash flow analysis indicates that the investment in a biomass cogeneration plant where the surplus chips are used for MDF production is economically feasible. The expected present value of this project is R$ 62.4 million for a required investment of R$ 52.7 million, which results in a net present value of R$ 9.7 million. This result suggests that the rational use of the wood residues that are currently discarded plants can increase value if investment is made in a cogeneration plant. Once this investment is made, an additional investment of R$ 10 million to connect the cogeneration plant to the electric power grid provides the firm with an option to switch outputs between MDF production and surplus electricity generation. Given that the cost of this switch option is known, the question remains whether the value of the option is sufficient to cover the R$ 10 million investment required.

In order to determine this value, we simulate 10,000 monthly energy prices over a 10 year horizon starting July 2013. We consider that the option to switch to energy generation will occur whenever the expected cash flows from energy sales are greater than the cash flow that would be earned from MDF sales. The value of this option is R$ 16.9 million, which indicates that capital investment in interconnection to the grid is warranted. The option is exercised 33.3% of the time in average as shown in Fig. 4, which illustrates the probability distribution of exercise.

A sensitivity analysis was also performed over the model in order to determine the impact of variations in the model input parameters, assuming a variation of $\pm 60\%$ over their base value. As shown in Fig. 5, as expected, the value of the option to switch outputs increases with the long term price of energy $\overline{S}$ and the frequency ϕ of the jumps. On the other hand, an increase in the speed of reversion η in the energy price model reduces the value of the option, since high energy prices will revert faster to the long term mean.

Table 5
Model parameters.

Parameter	Δt	η	σ	$\overline{S}$	ϕ	$\pi=\mu-r$
Value	1.00	0.0447	0.2856	151,424	0.1049	0.00787

Fig. 6 indicates that option price increases with the mean size of the jump $\overline{\kappa}$, but decreases with price volatility σ. This is an interesting and unexpected result, as a well-known characteristic of options is that their value increases with volatility due to the asymmetry in their payoffs. In our case, this is explained by the fact that energy spot prices in Brazil are bounded between R$ 12.00 and R$ 725.00. This upper bound limits the high energy prices that result from greater price volatility, while the lower bound is rarely reached and thus has little effect, which creates a reverse price asymmetry. Thus, while greater price volatility provides both lower and higher simulated prices, the price bounds affect the higher prices disproportionately compared to the lower prices, resulting in a lower average mean price. Since the value of the option to switch to energy sales is a direct function of energy prices, a reduction in these prices will reduce its value as shown.

5. Conclusion

We analyzed the feasibility of an investment in a biomass residue and natural gas cogeneration unit for a manufacturer of MDF wood panels that has the flexibility to choose the optimal

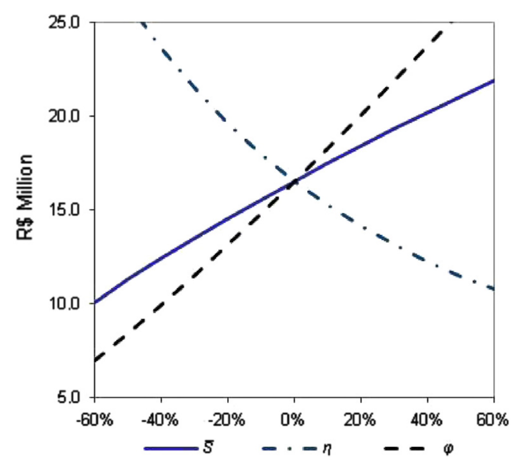

Fig. 5. Sensitivity of the option value (in R$ Million) for different levels of long term price, speed reversion and jump frequency.

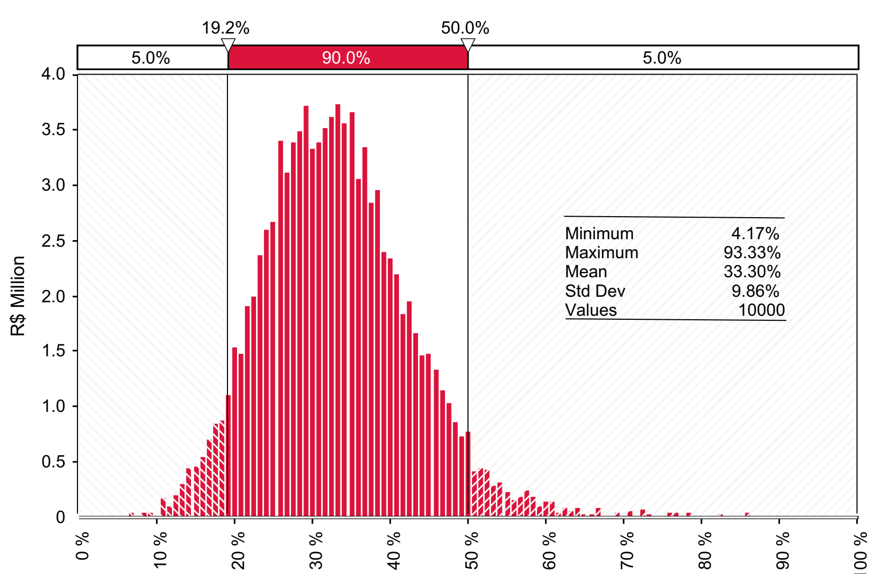

Fig. 4. Probability distribution of option exercise to switch to energy generation.

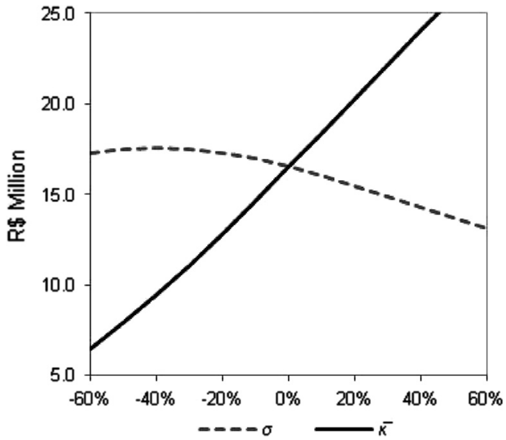

Fig. 6. Sensitivity of the option value (in R$ Million) to the volatility and size of the jump.

output from the eucalyptus chips currently used to generate thermal energy for the plant: production of MDF panels or surplus energy generation for sale in the short term market. The energy price was assumed to be the main uncertainty of the project and was modeled as a mean reversion process with jumps and a seasonality factor in order to better replicate the particularities of the Brazilian electrical energy market, which to the best of our knowledge is an original application.

The results show that the cogeneration plant is feasible even in a fixed operating mode where the wood chips previously used for generating thermal energy are fully applied to the manufacture of additional MDF panels, with an NPV of R$ 9.7 million. This indicates that aside from reducing the factory biomass waste, the rational use of these resources can add value to the project and to the firm.

An additional investment of R$ 10 million to interconnect the cogeneration plant to the power grid provides the firm with the flexibility to switch outputs, which increases the value of the plant by R$ 6.9 million. This value is derived from the firm's flexibility to divert the wood chips from MDF production to energy generation when energy prices are high. Sensitivity analysis shows that option value increases with long term energy price, frequency and size of jumps, and decreases with the speed of reversion and with electricity price volatility. This latter result is unusual and can be explained by the fact that energy spot prices are upper bounded.

The findings of this article may be relevant for managers in the industry that seek to maximize shareholder value and provide a more efficient use of their biomass resources. For policy makers who wish to determine public policies that foster greater use of renewable energy sources, wood biomass can represent an opportunity for a sustainable diversification of the Brazilian energy matrix with a renewable and non-perishable high density energy source.

The first limitation of this study is related to the restrictive assumption of a fixed price for the MDF panels, which was adopted due to lack of reliable data and historical price series. As previously mentioned, we assume that the most relevant project uncertainty are the future electricity prices, but parameter estimation of electricity prices is highly dependent of the length of the time series used and previous history may not be an accurate indicator of future prices. Given that the proposed technology route is well known and standard, additional uncertainties such as variations in capital expenditures, operational costs, and plant efficiency which could eventually impact the results were not considered as they were assumed to represent a low risk for the project and due to complexity issues.

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